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# Investigating the Electromechanical Coupling in Piezoelectric Actuator Drive Motor Under Heavy Load

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**Abstract** — The Piezoelectric Actuator Drive (PAD) is an accurate, high-torque rotary piezoelectric motor that employs piezoelectric stack actuators and inverse hypocycloidal motion to generate rotation. Important factors that determine motor performance are the proper concentric alignment between the motor ring and shaft and the similarity of the stack actuators used. This paper investigates the electromechanical coupling of these factors into the motor current through experimental means.

**Keywords** — motor, actuator, piezoelectric, piezo, stack, multi-layer

## I. INTRODUCTION

The Piezoelectric Actuator Drive (PAD) which can be seen in Fig. 1 is a type of rotary motor that transforms the linear motion of piezoelectric stack actuators into a precise rotational motion [1]. The operating principle is illustrated in Fig. 2. The micro-mechanical toothing present in the ring and shaft, shown in Fig. 3, enables high positioning accuracy and output torque [2]. This type of toothing combined with the inherent large stiffness of the piezoelectric stack actuators makes the PAD appropriate for voltage-driven open-loop control [3].

Due to its inherent structure, the PAD motor behaves like a fully capacitive, voltage-driven rotary machine. The piezoelectric stack actuators forming the basis of motion in this motor give it a capacitive nature. This, coupled with the reversibility of the piezoelectric effect enable the stacks to act as both actuators and sensors [4]. The current flow to the motor provides information about rotor speed and position, but also indicates the quality of mechanical contact between stator and rotor through electromechanical coupling between the shaft and the stacks.

The aim of this paper is to use current measurement from the piezoelectric stack actuators to describe and qualify the mechanical coupling between the motor ring and shaft under both heavy and no load conditions.

## II. MOTOR OPERATION PRINCIPLE

A piezoelectric stack actuator comprises of hundreds of individual piezoelectric layers separated by thin electrodes. A



Fig. 1: The Piezoelectric Actuator Drive (PAD)

voltage applied to the stack produces a proportional mechanical elongation. The layers are in a parallel configuration electrically, enabling a reduced voltage level to produce the necessary electric field. Mechanically, they are in a series configuration and therefore the elongation of each layer adds up to produce larger displacement than a single element would.

A widely-used model for piezoelectric structures is described in the IEEE Standard on Piezoelectricity [5]. A simplified version of the second alternative form of the constitutive equations given by the IEEE Standard are shown in (1) and (2), particularized for the dimension of actuation of a stack actuator. Stress in other directions is assumed to be null. Table I shows the quantities, their names and their units of measurement.

$$\Delta x = D_{33} \cdot V - \frac{1}{k} \cdot F \quad (1)$$

$$Q = C \cdot V + D_{33} \cdot F \quad (2)$$

TABLE I: List of constitutive equation symbols and their units

Symbol	Name	SI Unit
$\Delta x$	Displacement	$m$
$Q$	Stack charge	$C$
$V$	Applied voltage	$V$
$F$	Applied force	$N$
$D_{33}$	Piezoelectric constant	$m/V$ or $C/N$
$k$	Stack spring constant	$N/m^2$

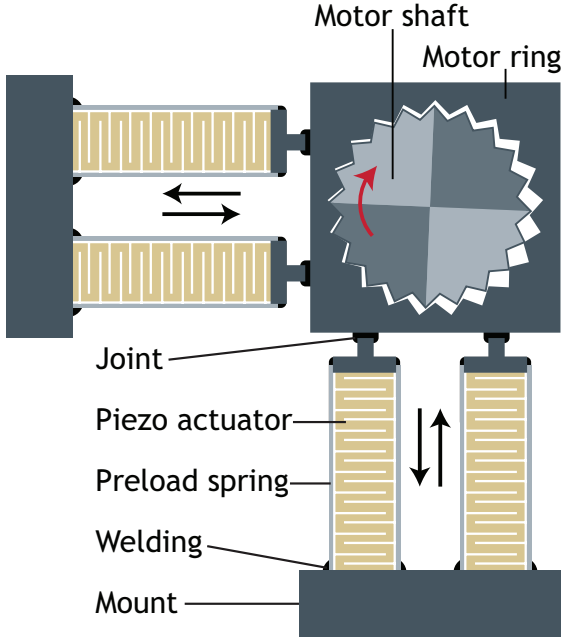


Fig. 2: PAD operating principle

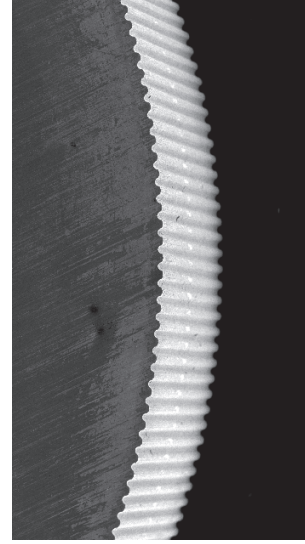
Two sinusoidal voltages with a  $90^\circ$  phase shift between them are applied to stack actuators placed orthogonally, as shown in Fig. 2. Thereby the motor ring moves in a circular trajectory defined by Cartesian coordinate pair  $(r_x, r_y)$ , expressed by the parametric equations (3) and (4). This will, in turn, produce a rotation in the motor shaft in the opposite direction to the ring.

$$r_x = x_1 \cdot \sin(2\pi f \cdot t + \phi_1) \quad (3)$$

$$r_y = x_2 \cdot \sin(2\pi f \cdot t + \phi_2) \quad (4)$$

Where  $x_1$  and  $x_2$  represent the elongation of the orthogonal stacks in m,  $f$  is the frequency of rotation in Hz and  $\phi_1$  and  $\phi_2$  are the phases in rad, with the restriction that  $\phi_1 - \phi_2 = \pm\pi/2$ . The trajectory produced is perfectly circular only if  $x_1 = x_2$ . This requires that the stack actuators are identical. Stack mismatch, improper shaft centering, hysteresis effects, and mechanical effects coupling into the motion will all produce deviations from circularity and in practice this will always be the case.

Every full rotation of the ring will cause the shaft to step one tooth. Therefore the relationship between the electrical and mechanical angular velocities  $\omega_{el}$  and  $\omega_m$  is shown in (5), with  $N_{shaft}$  and  $N_{ring}$  representing the number of teeth on

Fig. 3: Microtoothing on the motor shaft. Tooth distance is  $120\mu m$  and depth is  $38\mu m$ 

the motor shaft and ring, respectively.

$$\omega_m = \omega_{el} \cdot \frac{N_{shaft} - N_{ring}}{N_{shaft}} \quad (5)$$

### III. EXPERIMENTAL SETUP

The experiments were conducted using a PAD7220 produced by Noliac A/S, shown in Fig. 5. It contains two piezoelectric stack actuators on each actuation axis. They are represented by the red and blue rectangles in the figure. Their capacitance is rated at  $3.5\mu F$ . The rated motor speed is 56.7 rpm with a gearing ratio between ring and shaft of 312. Rated torque is  $4 N \cdot m$ . The applied sinusoidal voltages have an amplitude of 100 V and an offset of 100 V.

An oscilloscope and current clamps with a bandwidth of 50 MHz were used to acquire and log the motor current. Measurements were taken with the motor running at 60 Hz electrical speed, under conditions of no load and  $3 N \cdot m$  of load torque. A data acquisition window of 5 seconds together with a sampling rate of 200 kSa/s were used in order to capture accurate data for a full mechanical revolution. The block diagram of the test setup is presented in Fig. 4.

### IV. MEASUREMENT RESULTS

Analysis of the measurement data yields interesting results. The acquired data was first normalized for easier comparison between the loaded and unloaded cases. Fig. 6 and Fig. 7 show

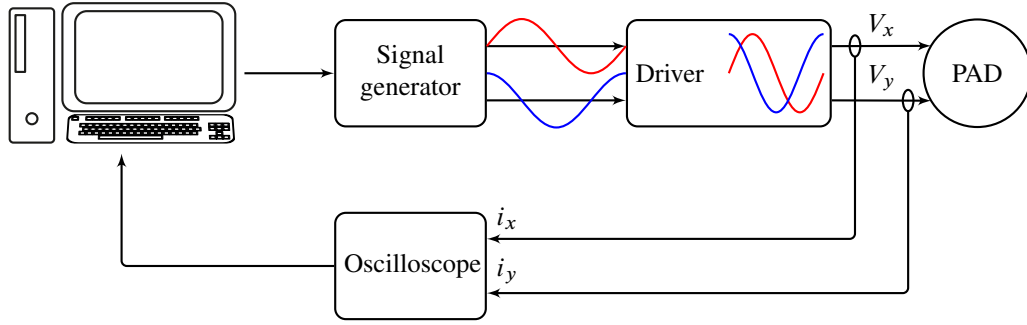


Fig. 4: Block diagram of the experimental setup

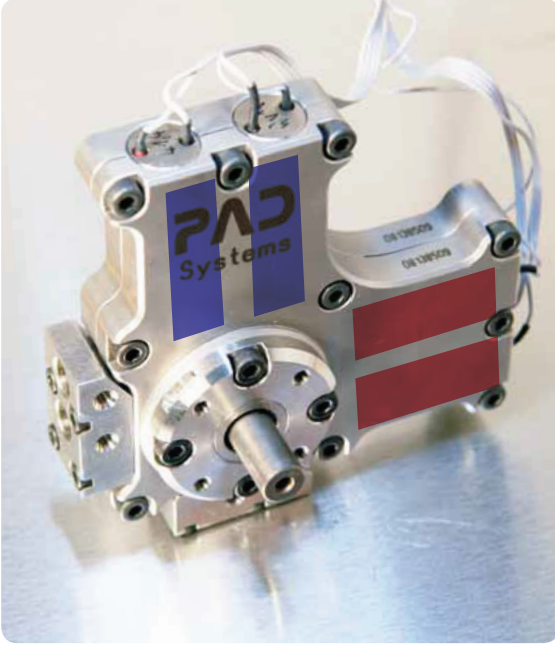


Fig. 5: The PAD7720 without the black cover. The stack ends are exposed: two on the  $X$  axis (red rectangles) and two on the  $Y$  axis (blue rectangles).

the trajectory of the traveling contact point between the motor ring and shaft during a mechanical quarter-circle motion. Each blue curve represents one electrical revolution and tooth step. The red pegs each represent one tooth on the shaft and help with visually keeping track of shaft position. The dotted black circles represent the ideal, undistorted trajectory.

The first observation is a pronounced deviation from circularity of the trajectory which is caused by lack of hysteresis compensation. Piezoelectric stack actuators are highly hysteretic [6] [7] and this effect can readily be seen in the contact point trajectory.

A second observation is the presence of a resonance in the case of the loaded motor which cannot be seen in the unloaded case. This resonance is the result of hard electromechanical coupling between the actuators and the shaft due to the high load applied to the motor shaft. This indicates that the motor is very close to its output torque limit, while also showing the absolute position of the weakest contact point – the starting point of the resonance. If load is increased further, a tooth skip

will occur at that point.

The lack of symmetry along the first diagonal of the trajectory plot further indicates that the loading on the stack actuators is not symmetrical. Specifically, the flattened region visible in both the loaded and unloaded cases in the lower right area of Fig. 6 and Fig. 7 suggests a lack of proper centering between the ring and shaft. The current does not increase as it should, therefore the stacks are blocked and cannot expand properly in that quadrant.

More information can be obtained by analyzing the single-sided amplitude spectra of the currents on both actuation axes with and without motor load. The input signals to the motor are ideally pure-tone phase-shifted sinusoids. Therefore, the ideal actuator response is also sinusoidal. The spectra, shown in Fig. 8 and Fig. 9 were computed over a full mechanical revolution of the motor shaft, meaning 312 electrical signal periods. By analyzing these signals, it becomes quickly obvious that a lot of energy is contained in the signal harmonics. The fundamental frequency mirrors the motor electrical speed (60 Hz), but harmonic components can be detected all the way down to the 92nd harmonic. This confirms the highly nonlinear response of the motor to input voltages.

Furthermore, since the input signals are purely sinusoidal, the quality of the motor response can be evaluated through signal-to-noise ratio (SNR), total harmonic distortion (THD) and signal-to-noise and distortion ratio (SINAD) analyses [8]. Table II presents the values obtained for each actuator axis, with the motor both loaded and unloaded. The SNR is higher under load than in the unloaded case. This is attributed to an increase in signal value while the noise floor is constant. The difference between the two axes in each case is consistent and further enforces the conclusion that the stacks are unevenly loaded. In all cases, the absolute values of the THD and SINAD measurements are approximately equal. This suggests that most of the distortion in the signals is harmonic distortion.

## V. CONCLUSION

The present paper uses empirical methods to investigate the effects of the electromechanical coupling between motor shaft and actuators in a PAD motor, under no load and loads of  $3\text{ N}\cdot\text{m}$ . The information contained in the trajectory plot of the ring-shaft contact point extracted from the normalized current measurements indicate rotor-ring misalignment as well as show the absolute position of the weakest point of contact.

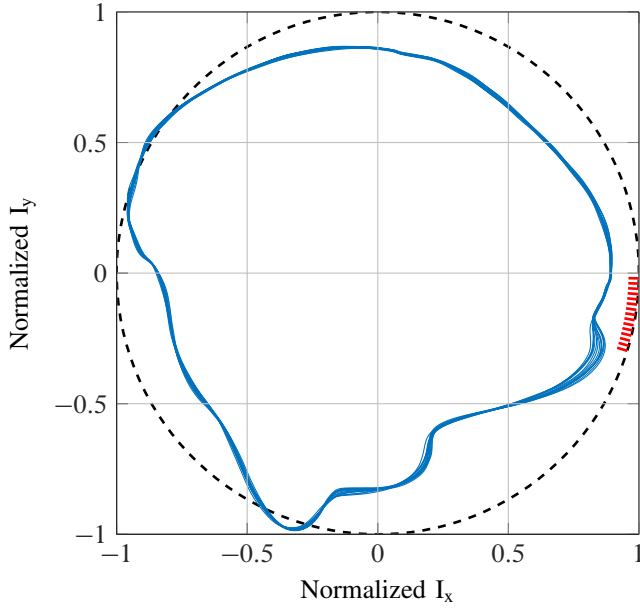


Fig. 6: Normalized contact point trajectory plot under heavy load (blue). The dotted circle is the ideal trajectory while the red pegs represent the number of teeth passed.

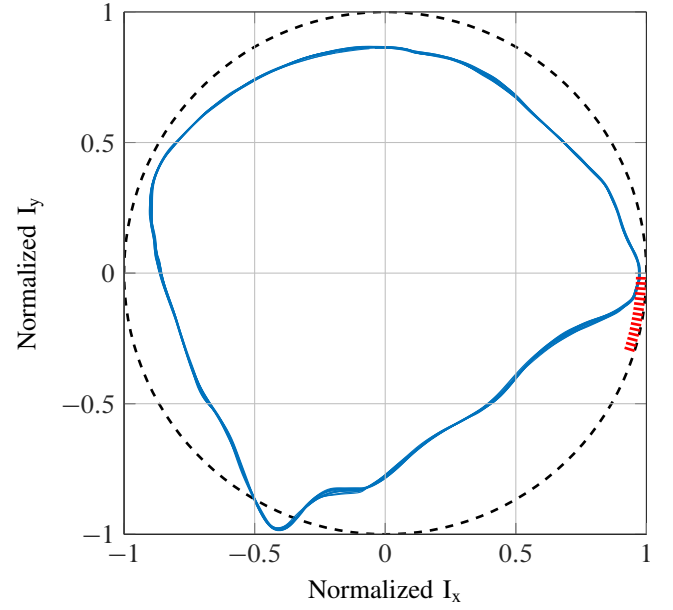


Fig. 7: Normalized contact point trajectory plot under no load (blue). The dotted circle is the ideal trajectory while the red pegs represent the number of teeth passed.

TABLE II: Values for SNR, THD and SINAD in loaded and unloaded cases

Case	Heavy load		No load	
Axis	X	Y	X	Y
SNR (dB)	37.895	40.625	35.079	35.897
THD (dB)	-17.367	-18.503	-17.638	-20.139
SINAD (dB)	17.365	18.543	17.561	20.059

Further analysis of the single-sided amplitude spectra of the stack actuators together with the current signal-to-noise ratio (SNR), total harmonic distortion (THD) and signal-to-noise and distortion ratio (SINAD) calculations enforce the conclusions drawn from the time and spatial plots of the current signals. These metrics also state that most of the distortion in the signals is harmonic distortion.

It was shown that the motor current carries a wealth of information about not only the loading effects on the shaft, but the quality of the mechanical assembly procedure. Moreover, the analysis can be conducted on any readily-assembled motor and therefore this a potentially useful tool in production quality assurance.

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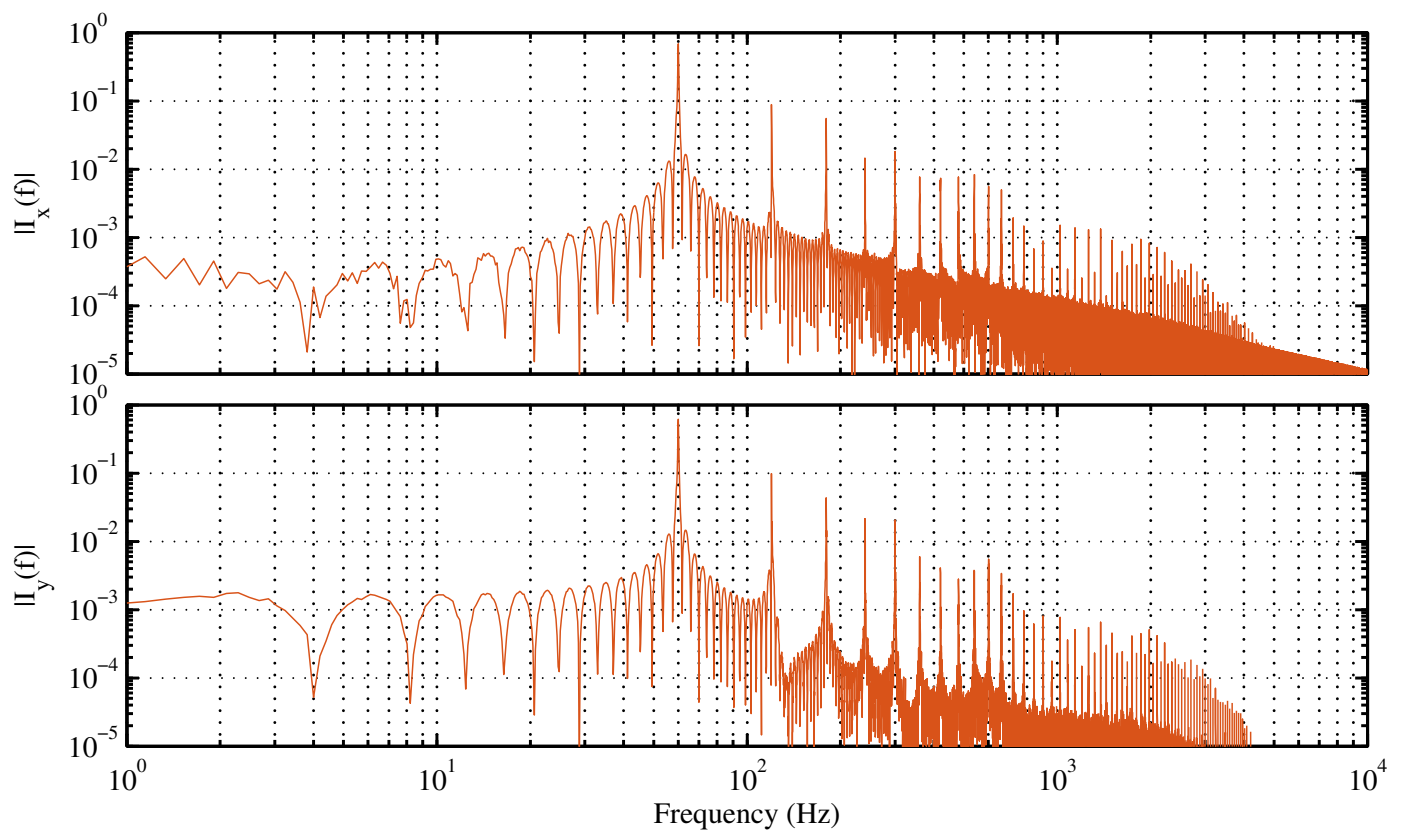


Fig. 8: Single-Sided Amplitude Spectra of  $I_x(t)$  and  $I_y(t)$  under heavy load

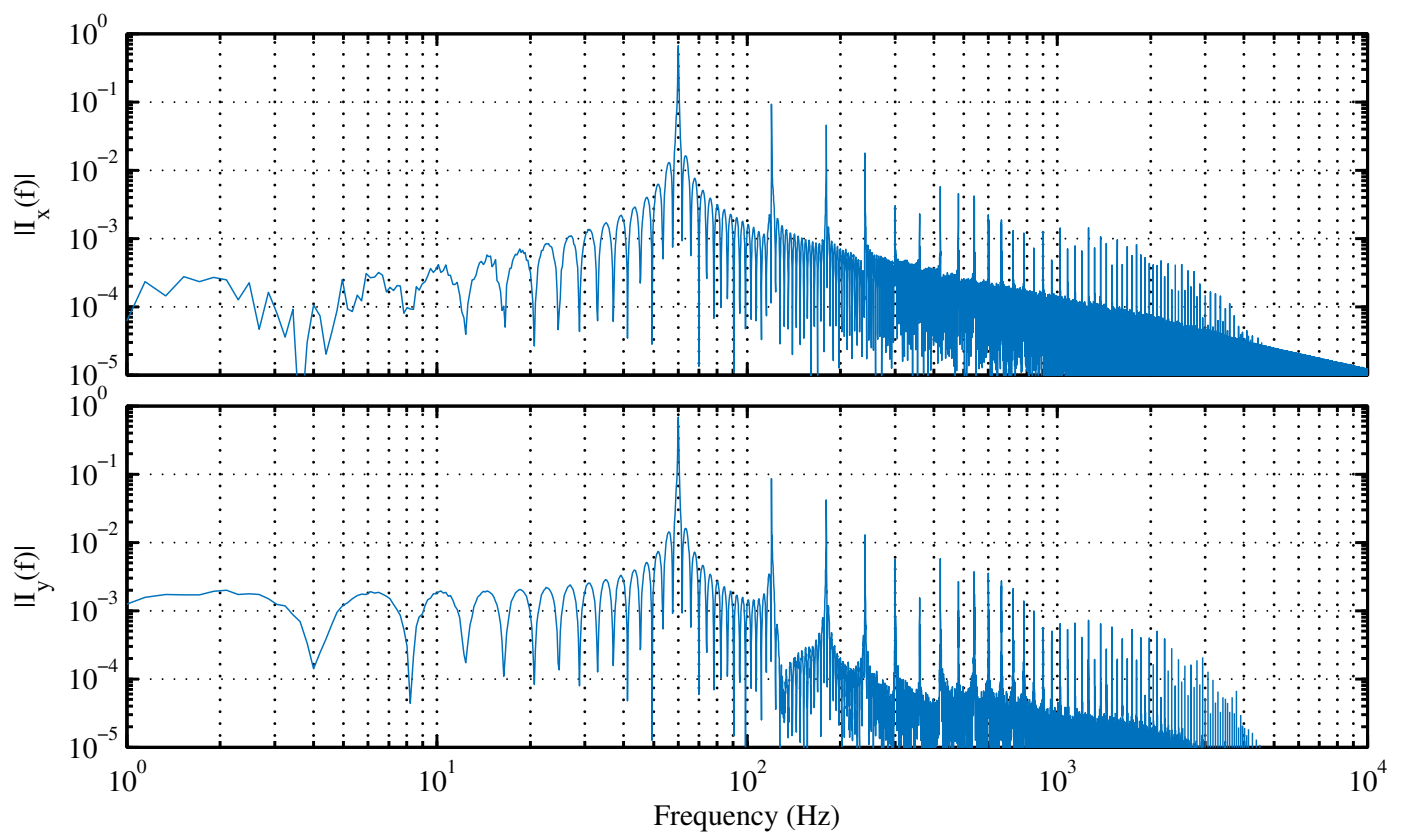


Fig. 9: Single-Sided Amplitude Spectra of  $I_x(t)$  and  $I_y(t)$  with no load